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(6 TRANSIENT EFFECTS IN JOSEPHSON JUNCTIONS

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I. INTRODUCTION

The unique switching characteristics of Josephson devices make them ideally suited for the numerous military applications of high speed logic elements that are anticipated to arise within the next decade. The fact that Josephson junctions simultaneously exhibit low power dissipation (a few microwatts), high speed switching capabilities (on a scale set by a few picoseconds), and can be reliably fabricated on a ten square micron size gives them unique advantages in comparison to present day technologies. For example, their small size and low power dissipation make them ideal for data processing systems that are confined to limited space, such as satellites. Furthermore, these properties combined with their high speed switching characteristics imply real-time signal processing capabilities that are demanded in ECM techniques such as radar jamming. In addition to these specialized applications, Josephson devices are also of general interest as switching elements in large scale, high speed computing machines.

These aspects of Josephson junctions were briefly discussed in the August, 1976, Monteray meeting on Applied Superconductivity, and it was clear that a conference devoted entirely to the switching properties of Josephson devices would be required. Accordingly, the Office of Naval Research decided to sponsor a two-day conference devoted to the switching, or more precisely, the transient characteristics of Josephson junctions. The objectives of this conference were:

1. Review the present state of the field with regard to both theoretical understanding and experimental accomplishments.

2. Discuss what new research objectives are required to best develop and exploit this new field.
3. Consider in greater detail the new physics and applications that are associated with transient properties of Josephson junctions.
4. Determine how studies carried out in non-equilibrium superconductivity bear on the problem of transient effects in Josephson devices.

In this report, we summarize the results of the conference.

The conference entitled "Transient Effects in Josephson Junctions" was held on March 24-25, 1977, and hosted by NOSC. In view of the fact that this was the first public meeting devoted to the switching characteristics of Josephson junctions, it was felt that the above objectives could be best accomplished by restricting the conference to a select group of about seventy leading scientists in the field of Josephson tunneling. The conference consisted of eleven invited and four contributed talks and was divided into three sessions: (1) Theory of Transient Effects; (2) Experiments and Applications of Switching in Josephson Devices; and (3) Non-Equilibrium Effects. As we shall discuss in this report, all of these sessions are related to one another. In Section II, the highlights of the conference are presented. Finally, in Section III, we report the major findings of the conference, its recommendations, and the future outlook of this exciting new field of research.

II. HIGHLIGHTS OF THE CONFERENCE

Until recently, research on the Josephson effects has centered on the junction's steady-state properties, although publications dealing with transient phenomena are now appearing in the literature. Thus, transient effects in Josephson junctions is a new field of scientific endeavor and the first two sessions of this conference were concerned with the present state of both theory and experiment as well as expected device applications. For example, in Session One, a new theory concerned with transient phenomena was presented. This theory, which is briefly discussed in Section II-1, generated a great deal of interest on the part of the conference participants. Numerous valuable suggestions regarding experimental verification of this theory were made and these are also briefly reviewed in this section. Session Two dealt with experimental results and device applications based on the unique switching characteristics of Josephson junctions. In addition, consideration was given to the ultimate limitations of Josephson devices as switching elements. This discussion was quite valuable as it helped to pinpoint those areas in which additional research is required. Finally, in Session Three, both theoretical and experimental applications of non-equilibrium superconductivity were presented. This field bears on transient effects in a number of ways which are briefly discussed in Section II-3.

II-1. Possible New Transient Phenomena in Josephson Junctions

We can best characterize the theory by recalling Josephson's original considerations on pair tunneling. We quote,

"It is natural to ask whether there exists behavior of two coupled superconductors that is intermediate between those characteristic of complete separation and complete union, in which the two parts influence one another a certain amount, but not enough to exhibit the phenomena of superconductivity to their fullest extent."

Based on the overwhelming success of Josephson's predictions, it is quite reasonable to inquire into transient situations in which the junction behavior is intermediate between the fully correlated Josephson state and two completely separated superconductors. In particular, we ask

1. Do there exist situations in which the behavior of two superconductors is intermediate between complete separation and a Josephson junction; in which the two parts influence one another a certain amount but not enough to exhibit the phenomena of Josephson tunneling to its fullest extent?

and

2. How do two superconductors pass from the uncorrelated state to the fully correlated Josephson state?

A theory designed to treat such processes was advanced by D. Rogovin and M. Scully. The theory considers situations in which a superconducting tunnel junction is initially maintained in the non-Josephson state and then allowed to evolve under its own dynamics via pair transfer and a variety of electromagnetic processes. It is shown that new physical principles as well as additional dynamical variables other than the Josephson phase are involved in the junction's behavior.

These talks generated a great deal of discussion, most of this being concerned with possible ways to obtain experimental verification of the theory. The major difficulty arises in preparing the junction in the required initial state and then removing the mechanism that

quenches the Josephson correlations. Several experimental approaches were discussed. Among these were

1. Construct a junction in which the Josephson effect vanishes at a temperature $T_J << T_C$ where T_C is the critical temperature of the superconductors. Then use a thermal probe or external radiation to raise the temperature above T_J (but below T_C). The two superconductors should now be uncorrelated.

2. Decorrelate the two superconductors via a random radiation field and then switch the field off.

3. Drive a point contact from a non-Josephson to a Josephson configuration acoustically.

Of the techniques mentioned above, (2) is regarded as the most feasible, although it is not entirely clear that the required state is reached. Calculations are presently being carried out to verify this point. Approaches (1) and (3) are also possible, but are much more difficult. This is especially true of (3), although this will clearly yield the desired initial state. Finally, a fourth approach involving the use of a magnetic field was shown to be incorrect.

The theory mentioned above is primarily concerned with transient phenomena when the junction is initially prepared in the non-Josephson state. We note, however, that it can be applied to transient problems in which the junction is in the Josephson state. Specifically, transient problems that involve switching from the zero voltage to the finite voltage state. In particular, it can provide a theoretical framework in which the role of transient noise, the effect of interaction between different switching elements, and other issues can be examined.

II-2. Experiments and Applications of Switching in Josephson Devices

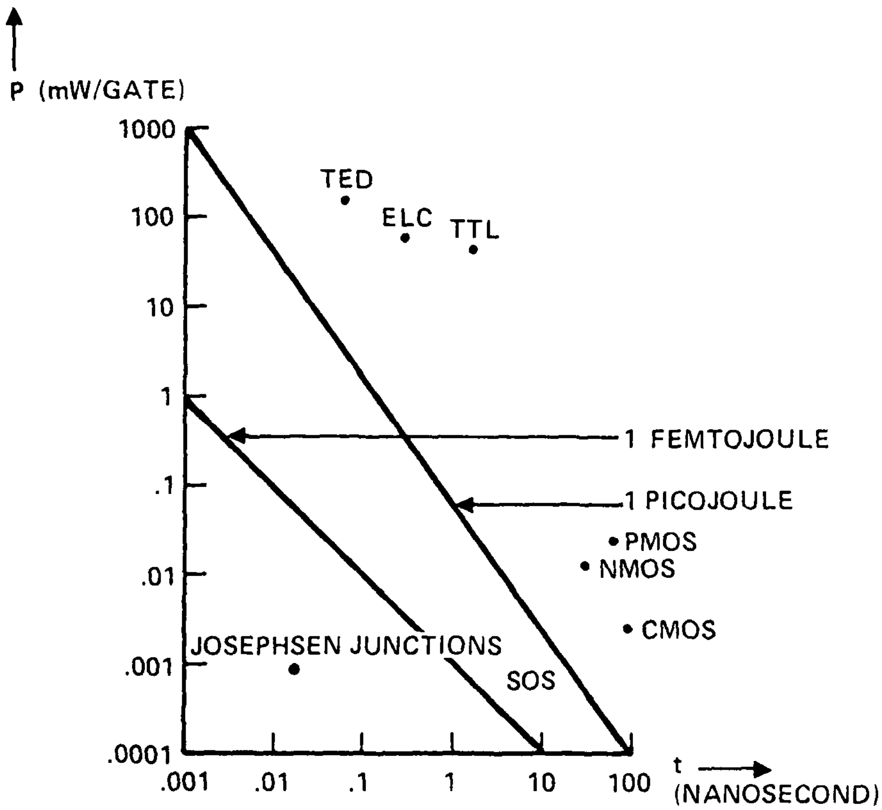
Session Two focused on the following topics:

1. The advantages of Josephson Switching Technology (JST) as compared to other technologies.
2. Significant application of JST.
3. The fundamental limitations of Josephson junction switching elements.
4. Experimental findings and presently available data on JST.

The usefulness of a particular device as a logic gate is set by its Pt value, which is the product of the power dissipated (P) with the logical delay time (t). The smaller the Pt value, the more attractive is the device as a switching element. To demonstrate the unique switching characteristics of Josephson devices, we have displayed in Figure (I) a performance chart which lists the Pt value for a variety of devices. An examination of this figure clearly reveals that Josephson junctions are extremely attractive as switching elements in comparison to other devices such as the SOS, P-MOS, and TED.

In addition to their ultra-low Pt value, Josephson junctions can be reliably fabricated on a ten to twenty square micron scale. The occurrence of all these features is unique to Josephson devices and as noted by A. Silver, D. MacDonald, and N. Welker, opens up opportunities in the fields of radar, satellite communications, electronic warfare, and data processing. These applications are briefly discussed below.

The unique switching capabilities of Josephson junctions make them an ideal candidate for an ultra-fast A/D converter. The



Pt PERFORMANCE CHART FOR LOGIC GATES

potential military applications of such a device are extremely exciting. For example, in ECM it should now be possible to perform real-time analysis of incoming signals and then either jam or deceive enemy radar capabilities. Due to their small size and low power dissipation, on-line data processing in space systems, particularly satellites, is feasible. This should present new opportunities in rocket signature identification as well as satellite surveillance in general. Finally, these devices are expected to provide large data storage capabilities which are highly advantageous in surveillance applications.

The fundamental limitations of JST received considerable attention at the conference. The properties of greatest interest are (1) switching time; (2) power dissipation; and (3) packing density. These characteristics are, to a certain extent competitive, and in device design trade offs will have to be made. We discuss this below.

We begin by noting that the switching time of the device is set by both the junction's RC as well as the plasma frequency. These times can be smaller than a picosecond, although at this point there is a trade off with current gain. Specifically the smaller the final state R_D (and therefore the larger the current inside the junction). the less is the current gain available for fan out processes. Thus, depending upon the specific situation, one must balance these two needs. Power dissipation is set by the Josephson coupling energy which is about 10^{-18} joules. This should be compared to conventional high speed devices which are 10^{-9} joules. Thus, for a chip with a packing density of 10^5 gates/cm^2 operating at a GHz,

the power dissipation for a chip utilizing Josephson junctions as switching elements can be as small as 10^{-4} Watts/cm^2. This should be compared to conventional high speed systems which dissipate about 100 Watts/cm^2. The usefulness of this to satellite surveillance, where the system must operate within narrow temperature limits, is obvious. The high packing density of Josephson logic gates is set by the present limits of electron beam (i.e., linewidth) technology and not by the intrinsic size of the device. In particular, junction sizes on the order of one square micron are sufficient for switching applications. Other limitations are dispersion on the wires which is small for 100 picosecond pulses, but a possible problem for ten picosecond pulses. Furthermore, various logic delays also arise, such as fan out delay, magnetic field penetration delay, as well as propagation delays down the superconducting wires. These delays can be dealt with in a variety of ways, but limit the overall switching time of the system. Finally, noise limits the sensitivity of these junctions, although large signal to noise ratios are generally expected to occur.

Experimental work is presently underway at IBM (Yorktown), Bell Telephone, Aerospace, NBS (Boulder), and various universities. At the present time the bulk of this work has been done at IBM, although other laboratories are rapidly obtaining results. The IBM effort was reviewed by H. Zappe and the following noteworthy achievements were reported: sub-nanosecond switching times, 10μWatt power dissipation, and circuits performing logic operations which perform on a nanosecond time scale.

Two switching techniques are presently employed: magnetic field switching (IBM), and current switching (Bell). At the present time, magnetic field switching appears to be the most advantageous, although this may present difficulties for high packing densities. Some of these potential problems are discussed in Section III.

Finally, T. Van Duzer discussed results involving the use of junctions that have semiconductor barriers instead of oxides. The advantages of such a system are low β_c values and resonance suppression. The disadvantages include more complex junction fabrication and high current densities are difficult to achieve

II-3. Non-Equilibrium Superconductivity

This session dealt with the properties of superconducting systems that have been driven out of equilibrium by an external source such as microwave radiation, quasi-particle injection, or heater phonon pumping. It is found that the non-equilibrium state is characterized by quasi-particle and phonon distributions that differ significantly from the well known equilibrium forms. Furthermore, in the presence of microwave radiation, Clarke has verified Scalapino and Chen's predictions of gap enhancement near T_C. In general, theory and experiment are in good agreement. Other topics covered include the performance of Josephson junctions at far infrared frequencies where heating occurs and non-equilibrium quasi-particle behavior in both squids and bridges. In general, theory and experiment are in good agreement and this field should be regarded as one of significant scientific importance.

Non-equilibrium superconductivity bears on transient effects in Josephson junctions in a number of ways. In particular, many of the features that characterize non-equilibrium steady-state will also appear in transient situations. For example, power dissipation due to switching of many junctions on a chip will drive the quasi-particles (in particular in the superconducting wires) out of equilibrium. Furthermore, it is clear that the effects of transient heating can be studied experimentally by the techniques used to examine the steady-state non-equilibrium properties of superconductors. Thus, it is expected that this research area will render considerable useful input into the study of switching properties of Josephson junctions.

III. CONCLUSIONS AND FUTURE OUTLOOK

The assertion that Josephson devices constitute extremely attractive switching elements is now an established fact. Specifically, the following research milestones have already been achieved:

1. Junction switching on a sub-nanosecond time scale.
2. Power dissipation on a ten microwatt level.
3. Reliable junction fabrication on a scale set by ten square microns.
4. Circuits that perform logic operations involving a number of Josephson junctions have been constructed and shown to operate on a nanosecond time scale.

Furthermore, the use of these devices as switching elements for both specialized as well as general applications is now a going program. This statement is underscored by the various research efforts, discussed at the conference, that are presently underway. For example, NBS (Boulder) is presently concerned with the construction of an A/D converter, whereas IBM (Yorktown) has a large effort in the development of ultrafast computers.

The conference clearly demonstrated that more research is demanded on a fundamental level if we are to fully realize the unique switching characteristics of Josephson junctions. In particular, one must understand these devices not only individually, but also collectively in the sense that they interact with one another. As a specific case in point, we note that the switching process will give rise to radiation emission and phonon generation. These fields will interact with the other superconducting elements, and both the quantitative and qualitative effects of these transient inter-

actions are not understood. Furthermore, we note that the fundamental limitations of Josephson junctions as switching elements will be determined, in part, by their transient noise characteristics. Now, although there exists a well established theory that treats fluctuations in steady-state, it is doubtful that this work applies to transient situations. For example, the nature of the voltage fluctuations during the transition from the zero voltage to the finite voltage state will depend upon the details of the transient process itself. Furthermore, signals propagating down the superconducting wires will also be subjected to a variety of fluctuations, and these processes have not been investigated. We note that the nature of the noise properties will depend intimately upon the switching time. For example, picosecond switching will be dominated by high frequency current and voltage fluctuations and it is likely that their spectra will display considerable frequency dependence. On the other hand, if the switching times are on the order of several hundred picoseconds, the spectra should be flat. We also note that it is not clear if one can characterize the noise as either shot or Johnson, and consequently its temperature dependence is unknown. Thus, the entire question of noise: its dominant sources, its thermal, temporal, and frequency structure, needs to be examined in detail.

The problem of pulse dispersion as the signal propagates down the superconducting wires has not been fully investigated. Thus, although dispersion is not a significant factor for pulses whose widths are on the order of 100 picoseconds or more, this is not true for ten picosecond signals. Specifically, such signals will contain frequencies on the order of the energy gap and it is well known that

the electrodynamic properties of all superconductors are strongly frequency dependent in this region of the spectrum. Furthermore, even at low frequencies the transient interaction between the thermally excited quasi-particles and the propagating electromagnetic pulses has not been fully investigated. Finally, little research has been carried out for modeling the external drive current into the junction, i.e., the battery. Such a model is clearly required if one is to obtain a thorough understanding of the switching characteristics of Josephson junctions. Furthermore, investigation into the switching characteristics which include the voltage dependence of the current amplitudes have not been carried out. To summarize, numerous fundamental properties involving noise, dispersion, transient heating, as well as collective junction effects are not well understood. These transient features will affect the performance of these devices and determine, in part, their fundamental limitations. These statements are especially relevant when considering more specialized devices that require elements that switch on the ten picosecond time scale.

Next, we discuss other areas of research which are of a more practical nature. For example, for devices based on magnetic field switching, one needs to know the spatial and temporal characteristics of the total magnetic field that arises from many junctions. Key issues here are:

1. What is the mean value of this field and what are the extremes it will reach in the course of time?
2. How often, statistically, will the field at a given point due to all the junctions, accidentally trigger a given junction?

3. What is the optimum current value to bias a junction at the zero voltage step? How does this value vary with the number of junctions in the limit of a large number of devices?

Another problem of significant practical importance is the effect of the interaction between the different superconducting wires on each other when they are carrying transient signals. It is well known that different current elements can interact with one another and it is important to determine whether these effects collectively add or cancel when there are a large number of active components.

As a given chip is used continuously, it will tend to heat up and it would be advantageous to determine the best substrate to use for system operation. In most circumstances, one would ideally like to remove this heat as quickly as possible. One approach would be to use materials in which phonons can rapidly escape. We note that aspects of this problem are under active investigation in research dealing with non-equilibrium superconductivity. Furthermore, we note that little research has been done in the area of overall system behavior, especially in the development of computer codes to treat many junctions on a given chip. Such a code should entail not only the switching characteristics of a single junction device, but should also simulate the behavior of 40-50 junctions during system operation. Such a number involves enough real estate to ensure a reasonable working knowledge of the statistical behavior of the entire chip so that one need not model all of the switching elements. On the other hand, a code that models only a few junctions will not be adequate to treat any collective effects that arise from the various interactions between the different system components.

Transient effects in Josephson junctions is a new research area with exciting payoff in both basic and applied science. Specifically, their unique switching characteristics form the basis for unusual device performance in the fields of surveillance, radar, space weapons, data processing, and high speed computing. Furthermore, the research reported in the first session of the conference indicates that the transient dynamics of Josephson junctions involves new phenomena that should be of considerable scientific interest.